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NASTRAN MODELING OF FLIGHT TEST COMPONENTS FOR UH-60A AIRLOADS PROGRAM TEST CONFIGURATION

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CASI

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Abstract

Based upon the recommendations of the UH-60A Airloads Program Review Committee, work towards a NASTRAN remodeling effort has been conducted. This effort modeled and added the necessary structural/mass components to the existing UH-60A baseline NASTRAN model to reflect the addition of flight test components currently in place on the UH-60A Airloads Program Test Configuration used in NASA-Ames Research Center's Modern Technology Rotor Airloads Program. These components include necessary flight hardware such as instrument booms, movable ballast cart, equipment mounting racks, etc. Recent modeling revisions have also been included in the analyses to the reflect the inclusion of new and updated primary and secondary structural components (ie. tail rotor shaft service cover, tail rotor pylon) and improvements to the existing finite element mesh (ie. revisions of material property estimates). Mode frequency and shape results have shown that components such as the Trimmable Ballast System baseplate and its respective payload ballast have caused a significant frequency change in a limited number of modes while only small percent changes in mode frequency are brought about with the addition of the other MTRAP flight components. With the addition of the MTRAP flight components, update of the primary and secondary structural model, and imposition of the final MTRAP weight distribution, modal results are computed representative of the 'best' model presently available.

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I. INTRODUCTION

1. UH-60A Airloads Program Review Committee Recommendations

Based upon the recommendations of the UH-60A Airloads Program Review Committee, which met with members of the various rotorcraft and flight test groups of NASA Ames Research Center in May 1990, work for a NASTRAN remodeling effort is conducted. The committee, including engineers and faculty from both industry and academia, suggested that a vibration survey of the UH-60A flight test airframe should be included as a complementary component of the continuing UH-60A flight test program. It was shown that in-flight vibration test data would be of minimal use unless a parallel commitment was made to a complete ground vibration test and modal analysis with accompanying finite element analysis of the flight test airframe configuration.

2. Additional Modeling of Flight Components

Previous UH-60A finite element modeling and ground vibration test efforts through Sikorsky Aircraft and NASA Ames Research Center have studied the changes in correlative results due to reconfigured mass distributions, secondary structure additions, and optimization tests. However, no direct study has been conducted to evaluate the current UH-60A Airloads Program Flight Test Configuration which includes additional structural or mass components and is unique and different in overall layout when compared to a baseline production vehicle. Analytical remodeling work for the addition/validation of structural and mass components is presented to support the Modern Technology Rotor Airloads Program and UH-60A test plan. This programming and work task was required to discretize the necessary structural/mass components to the existing UH-60A NASTRAN model in order to reflect the addition of flight test components and ballast currently in place on the UH-60A Airloads Program Test Configuration.

A study by the authors conducted previously using the a baseline UH-60 NASTRAN model [1] had included several secondary structural components, modeling revisions, and a mass distribution similar to that of the UH-60A Airloads Program Test Configuration (designated "NASA/AEFA"). The study consisted of a modal comparison using data found through ground vibration tests (GVT) and subsequent modal test analyses that were conducted by Sikorsky Aircraft using a *flight weight configuration henceforth denoted as "NASA/AEFA"* (preceding Phase I program flight tests at the U.S. Army's **A**viation **E**ngineering **F**light **A**ctivity, **AEFA** at Edwards Air Force Base, California). The NASA/AEFA GVT aircraft was tested for modal frequencies and shapes and compared with its NASTRAN finite element model counterpart. Previous undamped results showed significant differences in modal response data. These differences could be attributed, in part, to modeling assumptions made concerning the influence of secondary structural components. Secondary components such as firewalls, transmission bridge, cockpit doors, etc. were not part of the analytical model of primary structure. The authors denoted this primary and secondary structure model as **F**inite **E**lement **M**odel **I** or simply **FEM I**. An improved modal shape and frequency correlation was achieved with the addition of secondary components and several modeling revisions. (An example of this improved correlation using FEM I is presented in Table I.).

The current MTRAP test configuration of the UH-60A flight test aircraft is shown in Figure 1. This unique vehicle is dissimilar to the previously described NASA/AEFA configuration used in GVTs and its corresponding NASTRAN finite element model (FEM I) documented in previous reports. In addition to ***extra weight and ballast***, this flight test aircraft carries the corresponding ***structural flight test components*** such as instrumentation racks, ballast rack, ballast cart, etc. For this aircraft, a mass distribution different from previous GVT and NASTRAN model configurations is utilized. We also note that changes in stiffness due to these flight components have not been previously considered since they were not included in NASA/AEFA shake tests or analyses. Additional flight instrument components such as instrumentation systems and mounts have also been added since the previous NASA/AEFA GVT. A list of flight members contributing mass *and/or* structural stiffness to the UH-60A MTRAP flight configuration is presented in Table II.

A few of these components were deemed insignificant in contributing stiffness or mass to the model (ie. laser cube mount). However, many of these items have contributed a notable difference in dynamic response in conjunction with other components such as various instrument baseplates. This is particularly true of those items located on the cabin floor where a full ballast rack, ballast cart, and several instrument mounts add local stiffness thus affecting vibratory response. The role of other members in changing global dynamic response, such as the instrument boom and bar, needed to be ascertained. Both these members are mounted directly to frames and longitudinal beams in the forward cabin and cockpit. A majority of these members were added to the existing finite element model through the use of partial discretization approximations or fully discretized substructures that reflect their appropriate stiffness and mass effects.

Using a UH-60A NASTRAN model with secondary components, MTRAP flight components, and updates/revisions developed by the Sikorsky Aircraft Dynamics Group, the implemented modeling changes provide structural/mass agreement with the UH-60A Airloads Program Flight Test Configuration for future analyses and correlations with planned flight and modal tests. This accumulation of flight components and updates/revisions was called **FEM III**. This FEM III is the end result upon the completion of the three steps that will be described in a later discussion of basic model configurations.

In this report, the remodeling task and comparative analysis of an updated NASTRAN model discretizing the UH-60A Airloads Program Flight Test Configuration including various flight components is described. The most recent GVTs and updated NASTRAN models are also described in the following.

II. BACKGROUND

1. Design Analysis Methods for VIBrationS (DAMVIBS)

To understand the development of the UH-60A large scale finite element model, sufficient program background should be presented. With the U.S. rotorcraft industry's capability to accurately calculate static characteristics of helicopter fuselage structures, the even greater dynamic design problem of vibration prediction and control still remained in the late 1970's. One can restate the importance of significant and problematic vibration levels as they decrease overall vehicle performance and flight safety, increase maintenance efforts, and cause great concern in terms of human factors. On numerous occasions, inaccurate analytical predictions have led to costly "quick fixes" and unwelcome design compromises.

Several programs have contributed to the development of rotorcraft finite element models and their predictive capabilities. One recent advance in assessing the requirements for definitive vibration prediction and control came from Phase I of the completed DAMVIBS program. To achieve a superior capability in utilizing finite element models to support the Country's industrial design of helicopter airframe structures, NASA Langley Research Center sponsored the DAMVIBS program (**D**esign/**A**nalysis **M**ethods for **VIB**ration**S**) with industry and academia in between 1984 and 1991 [2]. As a result of this program, major technological contributions were given and received by the four industrial participants: Boeing Vertol, McDonnell Douglas Helicopters, Bell Helicopter Textron, and Sikorsky Aircraft. Each participant discussed, planned, and modeled a large scale finite element model of its own chosen production helicopter. Shake tests and modal test analyses were subsequently performed and correlated with the analytical model.

The results from this program indicate that significant deficiencies exist in the development of rotorcraft finite element models and their subsequent correlations with experimental results. It had also demonstrated the need for improved basic finite element modeling guidelines, efficient computational procedures, and commonly accepted methodologies in treating this unique structural dynamics problem. For specific experimental tasks such as the UH-60A Airloads Program, which has the experimental and theoretical characterization of rotor-fuselage coupling as one of the principal objectives, the DAMVIBS Program has given NASA engineers a baseline finite element model which can be improved and modified for special flight configuration studies and applications. We note that finite element model data from both the author's previous NASA/AEFA study and this current MTRAP study have been used by NASA and Army engineers for specific UH-60A analyses with rotorcraft predictive codes such as CAMRAD.

2. United Technologies Sikorsky Aircraft Contributions

Work with the UH-60A NASTRAN model is continued by the Dynamics Group at Sikorsky Aircraft in support of the existing production and also the design of advanced mission configurations. Sikorsky Aircraft's contribution to the DAMVIBS, NASA/AEFA, and MTRAP programs have come through its development and continued refinement of the UH-60A Black Hawk finite element model. Sikorsky's NASTRAN model of the UH-60A DAMVIBS baseline weight and primary structural configuration is the foundation and fundamental starting point for the current model. The Dynamics Group at Sikorsky Aircraft continues to maintain the development of the UH-60A finite element model through the inclusion of secondary structural components, the re-evaluation of mass, material, and geometric member properties, and the continued performance evaluation of the existing mesh discretization in support of its own engineering programs.

3. Modern Technology Rotor Airloads Program (MTRAP)

The UH-60A finite element model will serve an important role in the **M**odern **T**echnology **R**otor **A**irloads **P**rogram (**MTRAP**) in future ground vibration tests and flight test analyses. NASA and the U.S. ARMY are currently sponsoring this program with the participation of industry and academia to experimentally define vibratory airloads for the:

Validation of Computational Fluid Dynamics and Comprehensive Rotorcraft Codes
Investigation of Unique Flow Phenomena
Modernization of Industry Empirical Design Methods

Hence, a comprehensive database is being formed through the MTRAP alone to validate the techniques and methodologies required to improve the performance, dynamics, acoustics, and handling qualities of civil and military rotorcraft. A justification for this research consists of past acoustic, aerodynamic, aeroelastic, and interdisciplinary studies identifying rotor system vibratory airloads as the main source of rotorcraft noise and vibration.

The key element of the MTRA Program is the **UH-60A Black Hawk test plan** [1] (also known as the UH-60A Airloads Program) which will further contribute to the database through numerous flight tests, model scale, and full scale wind tunnel tests for rotor airload definitions in conjunction with the development of specific code applications for analytical predictions and correlations (ie. NASTRAN modal prediction/correlation). This remodeling effort of the NASTRAN model presented here serves as a complementary contribution to the UH-60A test plan. The completed NASTRAN model (FEM III) includes additional secondary structural components, an improved primary/secondary structure, flight test structural components, and a modified flight weight distribution as prescribed by the NASA/ARMY Modern Technology Rotor Airloads Program. Through the validation and continuing improvement of a predictive analytic model, a generic understanding of inherent fuselage characteristics may be achieved. Ultimately, their role within rotor-fuselage coupling behavior may be characterized and resulting overall vibration may be controlled in design.

4. Test Configurations

The principal objective of this applied research study is to address the need for an accompanying finite element model for both the current flight and ground vibration tests configurations. The planned shake test will be a NASA Ames in-house effort and is scheduled tentatively for late 1995 or early 1996. The planned shake test configuration will reflect the unique structural layout and weight distribution of the MTRAP flight aircraft currently involved in flight programs. This MTRAP configuration will be only one in a series of previously built-up ground vibration articles that have been analyzed including the first baseline DAMVIBS (**D**esign/**A**nalysis **M**ethods for **VIB**ration**S**) configuration and the NASA/AEFA weight distribution. A description and summary of their subsequent analyses of these articles is provided:

4.1 DAMVIBS

Ground vibration tests were performed in the DAMVIBS program using weight distributions resembling the UH-60A Airloads Program Flight Test Configuration. The baseline configuration of the UH-60A production aircraft or DAMVIBS configuration weighed 10,000 lbs and was among the first helicopters to undergo full-scale shake testing under the NASA Langley sponsored DAMVIBS program. UH-60A ground vibration testing for the NASA Langley DAMVIBS was conducted by Sikorsky Aircraft in Stratford, Connecticut. NASA/AEFA shake testing for the Modern Technology Rotor Airloads Program was performed in conjunction with similar tests for the DAMVIBS Program. We note that a finite element model of this baseline UH-60A had been developed for GVT correlation and comparison at this time.

4.2 NASA/AEFA

Soon after the baseline DAMVIBS UH-60A was tested for various modal response functions and parameters, equivalent masses of flight components were added at specific locations to duplicate the NASA/AEFA flight weight distribution and a retest was performed. We note that no adequate model describing the NASA/AEFA GVT or flight test configuration had been developed at this time. The NASA/AEFA GVT was conducted using this weight and baseline structural configuration. The NASA/AEFA GVT article is described as a flight worthy, government owned UH-60A helicopter (S/N 86-24507) with the following parts and equipment removed for GVT purposes [3]:

Main rotor blades	Tail rotor blades
Main rotor hub	Tail rotor hub
Spindles	Cabin troop seats
Bearings	Tail gearbox cover
Dampers	Intermediate gearbox cover
Bifilars	Nose absorber access cover
Lower pylon fairing	*Various aerodynamic fairings/covers
Fuel	

*Various aerodynamic fairings and covers were removed to allow access to measurement locations.

The presence of most secondary structural components intact in both DAMVIBS and NASA/AEFA GVT articles is noted. Also, the nose, forward cabin, and aft cabin vibration absorbers were rendered inactive. The following are installed in the NASA/AEFA GVT article:

Modified Black Hawk main rotor hub**
Main rotor head ballast
Main & tail rotor excitation hardware
Main & tail rotor suspension hardware
Dummy tail rotor hub

**640 pounds were added to the main rotor hub, in the form of shaker hardware and dummy steel plates, to simulate 50 percent of the flapping mass of the main rotor blades and bifilar mass. This additional mass *approximately* simulated the 4/rev rotor impedance of the UH-60A and consequently yielded test modes near 4/rev. The dynamic properties were therefore similar to the modes of an inflight aircraft which has frequencies in the 4/rev region.

To satisfy the NASA/AEFA flight test weight distribution requirement as defined by the NASA/AEFA flight test aircraft, a specific flight mass distribution was defined for the GVT article. The *equivalent masses* of the following flight components were added to the aircraft for modal testing as seen in Figure 2:

Pilot
Copilot
Ballast
Full Fuel
Instrumentation Racks (3)

One notes that these additions to the GVT article effectively change mass distribution only (ie. the stiffness contributions from the addition of true flight test components such as instrument racks, ballast rack, etc. is not reflected in GVT data). Due to this fact, subsequent NASTRAN modeling and analyses emphasized modeling these masses to achieve better correlations with GVT data. Thus, one sees a need for a ground vibration test using all flight test components. The sole difference between the NASA/AEFA and DAMVIBS GVT configurations is the addition of the component masses mentioned above. The NASA/AEFA shake test configuration weighs approximately 17,800 lbs with the addition of the seven components, while the base DAMVIBS shake test article weighs 10,140 lbs. It is not expected that the DAMVIBS or NASA/AEFA NASTRAN models will achieve accurate correlations with the planned shake test of the UH-60A Airloads Program Flight Test Configuration because that test has yet a third configuration.

4.3 MTRA Program

The MTRAP or UH-60A Airloads Program Flight Test Configuration expands on both these previous weight distributions of the baseline UH-60A particularly that of the NASA/AEFA weight configuration. The MTRAP configuration has a unique weight distribution and structural layout corresponding to the maintenance of a constant center of gravity under flight conditions, telemetry and data gathering equipment, and other objectives such as are mentioned in a preliminary Longitudinal Centroidal Gravity Expansion Program. The 1995 shake test configuration will include relevant flight test structural components, equipment, and those additional ballast weights related to the flight aircraft and its previous flight test objectives.

III. MODELING APPROACH

1. Basic Model Configurations for Study

Three basic model configurations have been considered throughout this study. Each of these models reflects a separate stage of improvement between the previous study by the authors and the most current or 'best' model available that is of greater interest. Throughout this study, the completion of the unique UH-60A Modern Technology Rotor Airloads Program (ie. MTRAP) Configuration is of primary importance. The three basic **F**inite **E**lement **M**odel (**FEM**) configurations are described and denoted as follows:

FEM I. A Primary/Secondary Structural Model

FEM II. The Primary/Secondary Structural Model with MTRAP Flight Components

FEM III. A final Updated and Revised Primary/Secondary Structural Model with MTRAP Flight Components

First using **FEM I**, the primary and secondary structural model previously used by the authors in the September '90 study of the NASA/AEFA Configuration and secondary structural additions is modified down to two pre-defined starting reference configurations that vary with respect to mass distribution. In the second step, these two starting reference configurations are used respectively in the **B**uild-**U**p of **C**omponent **S**tructure and **B**uild-**U**p of **C**omponent **M**ass **S**tudies (henceforth denoted as **BUCSS** and **BUCMS** respectively) giving **FEM II** upon completion to determine the influence of components on an individual basis. With this step, a check-out of the MTRAP flight components is completed. Finally, updates and revisions that have been made to the full primary/secondary structural model by the Dynamics Group at Sikorsky Aircraft as of November '92 are brought together with the MTRAP flight components and their unique flight mass distribution to constitute **FEM III** or the 'best' model available. A list of items that are accumulated as a result of each of these three steps is presented in Table III.

2. Modeling Approaches

A basic guiding philosophy is followed in this study with respect to the modeling of these flight components. The modeling guidelines define the minimum model that will accurately discretize each flight component. In the end, a modified and equivalent stiffness matrix is required that is characteristic of the additional component stiffnesses. A modified and equivalent mass distribution is also required.

3. Rigorous Geometric Model vs. Equivalent Stiffness Approach

One should differentiate between the two finite element approaches that can be used to simulate the behavior of an additional dynamic component. The finite element method is viewed as successful in that a *rigorous geometric model* with accurate cross sectional, material property data, and an appropriate grid point and element mesh can define the physical component being modeled and generate the associated mass and stiffness matrices. To simplify the modeling effort, one may also consider the significant dynamic and static stiffness influences of additional components when added to a global physical model and include them such that an *equivalent stiffness* and mass matrix is modeled and the dynamic and static responses are equivalently simulated. In this case, those parts of the flight components that are considered to be the main structural and mass features are modeled by modifications to the existing mesh. Such modifications may include the re-computation of a 'composite' cross section and material which represents the overlap of the added component on the primary structure.

In considering the UH-60A finite element model, three general approaches are used to include the additional stiffnesses of the more complex flight components:

1) Full discretization of each flight component.
2) Equivalent and partial discretization of the flight component
3) Modification of existing mesh to account for additional stiffness

These are described as follows:

3.1 Full Discretization of Each Component

In this method, the flight component to be modeled is discretized by a mesh that accurately depicts the geometric domain of the component. The mesh is made with a similar order or fineness as the existing global mesh of the UH-60A. An appropriate grid point and element numbering system that is non-coincident with any systems in the global model is assigned. Cross sectional properties such as neutral axis locations, and area are determined through design or manufacturing blueprints or computed. Material properties and other complementary data are similarly gathered or computed.

We note that the existing mesh of the UH-60A is not highly refined but is sufficiently advanced to allow an estimation of low frequency modes below 20 Hz. Any mesh order developed for flight components that is significantly higher than that of the global model would not contribute in a positive way because the global response of interest will perform only as accurately as its weaker formulation (namely, the lower order mesh of the existing model). The modeling of the Trimmable Ballast System (TBS) Ballast Rack is an example of this approach.

3.2 Equivalent and Partial Discretization of Flight Structures

An equivalent or partial discretization of a flight component structure may also be performed to account for the projected types of modes and basic flexural action of the components. In this case, the modeler is asked to determine the principal structural members and mass features of the components that contribute most significantly in terms of stiffness and mass effects. These main structural and mass features are modeled exclusively as well as the tie-down points of the components to the primary structure. The less important structural features of the components are combined together with significant mass items as they are not considered to contribute significantly to the dynamics of the component relative to main structures.

The modeling of the Flight Engineer's Instrumentation Rack in the forward right-hand section of the cabin is one such component that requires this modeling approach. The instrumentation rack shelves and cover are composed of very thin sections. The rack itself, however, is supported by two T-section beams that are attached to the top and bottom half of an aircraft frame. The attachment of the T-section beams is made with two L-beams that fasten the top and lower ends of the two T-beams to the frame. These T-section and L-beams are the main structural features while the instrumentation rack's thin cover sections and light equipment loads are considered to be the important mass item. Using an approach where an *equivalent or partial discretization* is required, structural beams and angles are modeled while the instrumentation rack cover and thin walled structural cover and shelves are distributed as mass.

3.3 Modification of Existing Mesh

Another approach is the local modification of the existing global mesh by accounting for changes in the area moment of inertia, modulis of rigidity, and structural configuration that are due to an additional component. While *convenient in terms of geometry and program modification*, this is the *least flexible or stiffest* estimate of the three methods for enacting model modifications. In this method, the modeler modifies the existing mesh of the global model to allow for the superposition of a component model. New area moments of inertia and material properties are then calculated to include the superposition of the component (as in the computation of a cross section consisting of one or more different sectional areas and isotropic materials). Such an approach is elaborated upon in the following example and compared with a full discretization approach.

4. Case Example: Ballast Rack

To incorporate the structural and mass contribution of an additional component to a global finite element model, several approaches can be used. One approach requires the tuning of existing finite elements (modification of existing mesh) in the global model in order to simulate the additional stiffness and weight associated with an added component. Another approach requires the full finite element discretization of the component in a scale appropriately fitted to the global model and a reasonable estimate of the displacement boundary conditions (such as those representative of cabin tie-down points). Clearly, both approaches have their limitations as will be shown. One will find that although a modification of the existing mesh is an easier approach, limitations encountered in terms of geometry of the existing mesh warrant the full discretization of the added component.

In a method requiring the modification of the existing mesh, we consider the example of the addition of the Trimmable Ballast System ballast rack to the UH-60A cabin floor to illustrate the approach. The following steps are carried out. First, the geometry, node points, and material properties of the cabin floor elements are found using model data. Second, the geometry and material properties of the ballast rack are defined. A graphical overlay of the ballast rack over the cabin floor is created at this point to determine which cabin floor finite elements require tuning. If the overall shape and geometric details of the ballast rack are not coincident with elements in the cabin floor mesh, modifications to the mesh is made. Element properties are then recalculated to account for the new combined geometric and material cross sections which result in an equivalent stiffness model representative of the ballast rack. These elements are fixed to the cabin floor.

In a method utilizing a complete finite element discretization, we again consider the working example of the ballast rack to the cabin floor to illustrate the approach. The following step are carried out. As in the previous method, the geometry and node points of the cabin floor elements are found using the model data. Second, the geometric, material, and cross sectional properties of the ballast rack are defined as are any required tie-down point or displacement boundary conditions. A graphical overlay of the ballast rack over the cabin floor is created again but is instead used to determine where tie-down points of the fully discretized ballast rack would require companion tie-down points on the cabin floor mesh. If such node points on the cabin floor mesh are not geometrically coincident with the corresponding tie-down points of the ballast rack, the existing floor mesh is modified. Lastly, a discretization of the ballast rack of mesh order similar to that of the cabin floor is developed with appropriate tie-down node points. Displacement boundary conditions at these node points are specified to connect the added component to the global model. In this approach, proper displacement conditions are required to bring about an equivalent stiffness model representative of the ballast rack which is fixed to the cabin floor only at the tie-down locations.

Clearly, each approach has its advantages and disadvantages. If one requires the tuning of existing finite elements which is easier to implement, the shape of the global element mesh coincident with that of the component mesh is required. This is often not the case when the component mesh consists of elements that are angled and have shapes characteristic of complex cut-outs (as in the case of the ballast rack). This approach also assumes that the component acts as a one-piece composite with the component mesh. We note that displacement boundary conditions as exhibited by characteristics such as tie-down points of the ballast rack to the cabin floor are not considered in this easier approach. Equivalent boundary conditions in this respect assume that all component mesh nodal points will share the same kinematic history as those of the coincident global mesh.

Similar disadvantages can be seen in the approach where a full discretization of the component is required. The complete component model with nodal points defining tie-down locations requires coincident nodal points on the attaching global mesh surface. However, modifications to achieve this can be performed on the global mesh without effecting changes that are unrepresentative of the mesh stiffness such as a local mesh refinement. Through this approach, a correct component stiffness model and proper displacement conditions can be defined. Thus in viewing a 'composite' action versus direct stiffness approach, one sees that due to the geometry of the existing global mesh, that the full discretization of additional components and appropriate boundary conditions is warranted in the practical component modeling effort and build-up study that is presented here for a majority of the components. In the case of the ballast rack and a majority of the structural flight components, a full discretization was used.

5. Additional Modeling Considerations

There are other aspects of this component modeling that require consideration. The order of the grid point and element mesh should be considered. A poor selection may produce an overstiff mesh and modal behavior uncharacteristic of the physical interaction between global and local component meshes (ie. interaction between cabin floor and ballast rack.). We also note that mesh refinement must be gradual as one moves from a low number of elements in a given region to a much higher number of elements in an adjacent region while maintaining necessary tie-down grid point definitions and the accurate discretization of the component. A non-gradual refinement may lead to excessively large stiffness terms compared to surrounding terms in the stiffness matrix. This leads to the possibility of an ill-conditioned matrix, a poor problem formulation, and subsequent incorrect eigensystem solution. Attention has also been paid to ensuring the best and most proper element sizes and tapers, definition of tie-down points, and acceptable component discretization in each flight component case for the global model.

We also note that an effort in generating a high order mesh for the global or local component model is driven by an interest in a large number of response locations in the component or in very accurate modal frequency or shape results regarding the component mesh itself. Fortunately, we are interested in global response to a larger degree rather than specific local response. Thus, details regarding the generation of component grid point and element mesh, within correct physical modeling principles, may be guided by the overall interest in the global helicopter fuselage response.

We note that in this limited study many experimental verifications of the individual flight components were not conducted. For example, the accurate discretization of each component was not verified with experimental strain or modal tests. Such a validation is recommended in any future GVT study.

Other modeling aspects were considered as one moves the component from blueprints or manufacturing plans to its respective element discretization. The determination of coordinates specifying the neutral axis is important as it determines the respective area moments of inertia. This evaluation of the neutral axis is unique for each structural bar, beam, or tube member and depends on their connection to the global fuselage model and primary flexural action of the component. The determination of important element properties is also required including cross sectional areas, moments of inertia, material properties, Young's modulus, mass density, and the accurate definition of tie-down points.

6. Summary

Clearly, several approaches were considered in the modeling of each additional flight component. The approaches involved in the finite element modeling of these components are summarized by three methods: 1) A *full discretization* that equivalently brings about a stiffness matrix representative of the component, 2) A *partial discretization* of the component that equivalently brings about a stiffness matrix characteristic only of the significant flexural parts of the local component, and 3) The *modification of the existing mesh* to model the 'composite' flexural action of the component plus the global structure mesh.

It will be seen in the following sections that a full discretization (method 1) was warranted in most component cases, although a partial discretization (method 2) is sufficient in at least one case (ie. flight engineer's instrumentation rack). *Alternatively*, although method 3 was not used in this study, a modification of the existing mesh was deemed as a fair and flexible approximation that was easier to implement when the similar component and global mesh geometries were similar. While a modification of the existing mesh to form an equivalent stiffness is simpler to implement for any single component, it may not be convenient due to limitations set by the pre-existing or even nonexistent global mesh geometry that shares locality with the component. In all three approaches, a correct definition of displacement boundary conditions between components and the global mesh are an area of concern.

IV. PRIMARY/SECONDARY STRUCTURAL SYSTEMS

1. Objective

The final results of this study encompass the incorporation of three important finite element model parts in terms of structural contribution and weight distribution. Each of these three have been included in the FEM III or the 'best' model currently available. These include:

1) Primary Structural System
2) Secondary Structural System
3) Flight Components

These systems are reviewed in the following:

2. Primary Structure

The first structural system describes the **primary structure** of the rotorcraft fuselage exclusively. Generically defined, primary structures are components that are designed to be load carrying members. The primary structure consists of aluminum semi-monocoque structures including frames, stringers, skins or panels, beams, and bulkheads. In areas of high temperature or concentrated load, titanium and machined parts are used. The finite element model for this primary structural system is composed of 8,803 elements, specified geometrically by 4,669 grid points, and utilizes 25,509 degrees of freedom (DOF) as presented in Figure 3. The primary structure represents a baseline UH-60A aircraft at 10,000 lbs. By using dynamic reduction methods, the number of global DOF's are decreased to 77 modal coordinates. This primary structure is included in FEM I, II, and III.

3. Secondary Structure

The secondary structural system combines both the **primary structure and specific secondary structural components (FEM I).** Generally, glass, plexiglass, fiberglass, and kevlar coverings or skins fall into the secondary structure category. They are generally formed in a composite sandwich construction made up of aluminum honeycomb cores with laminated fiberglass or kevlar skins. In some areas, the aluminum core is not used with the fiberglass and kevlar skins. The windows in the mid-cabin and side cockpit are stretch plexiglass. The windshields, which have wipers, are laminated glass inside with an outside layer of PVB plastic. In addition to the selected secondary structural components, several modeling revisions were included to correct physical and material properties of the former primary structure model by Sikorsky.

Many of these modifications were motivated by Sikorsky studies using a nonlinear programming code called PAREDYM (PArameter REfinement of DYnamic Models), which identified changes required in a finite element model to yield improved correlations with GVT results. To satisfy the flight weight distribution as was done in the NASA/AEFA GVT, the following *equivalent masses* of several flight components were incorporated by the authors into the mass discretization of the UH-60A NASTRAN finite element model:

Pilot
Copilot
Ballast
Full Fuel
Instrumentation Racks (3)

We note that not all flight test instrumentation components are modeled in terms of mass and structural contribution (such as are found in the current MTRAP configuration and study). Depending upon the flight test objectives, some components are included as ballast payload in a number of locations throughout the longitudinal length of the helicopter. Possible ballast payloads and their respective locations are presented in Table IV under the general arrangement for the longitudinal center of gravity expansion program which has set aside a series of pre-determined mounting surfaces in the UH-60A aircraft where additional ballast can be placed for various flight test purposes.

The primary and secondary structural system is discretized by 9,185 elements, geometrically described by 4,842 grid points, and requires 26,547 DOF's as presented in Figure 4. One can compare these model attributes to those of the primary structural system alone which had 8,803 elements and 25,509 DOFs. Thus, the addition of secondary structure brought about an additional 382 elements and 1,038 DOFs. By reduction methods, the number of DOF's are decreased to a smaller modal subset. This NASTRAN model has an equivalent weight of 17,660 lbs (including lumped masses of pilot, copilot, fuel, ballast, and instrumentation racks).

4. Flight Components

Flight components unique to the MTRAP Flight Test Configuration were added to two versions of the primary/secondary structural model. The first version is a model used by the authors to study the NASA/AEFA GVT configuration in September of 1990 and was used currently to study the BUCSS and BUCMS. The second version is a recently updated version of the UH-60A including material property revisions and updated primary and secondary structural components and will constitute FEM III or the 'best' model (Figure 5). Flight components have been included in FEM II and III only. The evaluation and modeling of flight components are discussed in the sections to follow.

V. FLIGHT COMPONENTS

1. Evaluation

The first step of this modeling effort began with the determination of those significant structural and mass components on the flight test aircraft that required modeling based on physical modeling principles. A list of those flight test components that are unique to the MTRAP configuration, not found on previous baseline configurations of the UH-60A, has been generated with a complete description of the individual components and their test purpose. Reference materials including blueprints and physical measurements were gathered to aid in the evaluation of the listed components [4]. Best estimates of material and physical dimensional properties were made regarding those components fabricated at the Army Engineering Flight Activity, Edwards Air Force Base during 1986 flight tests as no formal design and manufacturing plans were made. Assumptions were then made as to the significance of the contribution of these components in terms of structural stiffness and mass. Those components that significantly contribute stiffness to the overall structure and its resulting structural dynamics were individually modeled. Smaller structural mountings were considered negligible in this respect, although the weight of all flight components were incorporated.

It should be noted at this point that no effort was made to estimate or incorporate damping contributions of these components. Critical damping ratios of the individual global modes may be measured in future modal testing planned and used to revise those modal frequency estimates that are to be presented here.

2. Description of Flight Components

For this finite element model, flight components were categorized into different groups based on their location within the UH-60A or their structural or weight contribution to the fuselage response. For purposes of clarity in such a categorization, each flight component were defined in only one of the following categories:

External Structural Components
Internal Structural Components
Mass Items

External Structural Components are those structures that are mounted to the exterior frames or shells of the aircraft and contribute in some manner to the overall stiffness characteristics and weight distribution. Physical test equipment items which fall in this category are for example, the instrumented test boom and LASSIE bar. These external structural components are seen in Figures 6 and 7. Analogously, *Internal Structural Components* are those items found inside the UH-60A fuselage (ie. cabin, cockpit, etc.) that contribute structural stiffness and mass to the fuselage response. The physical test items that are categorized as Internal Structural Components are presented in Figures 8 through 16. *Mass Items* are those components that have been deemed as contributing to the weight distribution exclusively and negligible stiffness. They are henceforth modeled as a single or series of concentrated point masses in the finite element analyses regardless of their internal or external location. Physical items that fall into the category of mass items are seen in Figures 17 through 20. Each component is described in the following section. Please note that item locations are described in a standard aircraft coordinate system (units in inches) with fuselage station, butt, and water line notation. The origin is denoted forward of the nose of the aircraft (beginning with the main rotor blade forward tip), level with the cabin floor, and symmetric about both halves of the rotorcraft.

2.1 External Structural Components

A. Instrumented Test Boom

An instrumented test boom is attached to the forward right side of the UH-60A underneath the cockpit door and forward cabin (Figure 6). The test boom length is 152.4 inches. The test boom includes a swiveling pitot-static tube and angle of attack-sideslip vanes at the front of the boom. The long boom consists of a series of welded and/or threaded structural tubes of various diameters and thicknesses. Two separate multi-bolted connection webs attach the complete boom assembly to aircraft frames at fuselage stations 247.0 and 188.0. This assembly was fabricated at AEFA for 1988 flight tests. The weight of the instrumented test boom is calculated to be 22 lbs including forward instrumentation and the two mounting assemblies that attach the boom to the airframe. This item was modeled with a full discretization.

B. Instrumented LASSIE Bar

Additional external instruments are required in MTRAP flight tests. An instrumented bar has replaced the pre-existing FM antenna at the cockpit door opening on the starboard side (Figure 7). An Elliot Low SenSing and Indicating Equipment (LASSIE) assembly is placed at the top of this bar. The LASSIE bar is considered to contribute very minor structural stiffness and mass to the global model. This assembly was previously fabricated at AEFA for 1988 flight tests. The self-weight of the LASSIE Bar is calculated to be 10 lbs including the accompanying LASSIE instrumentation. This item was modeled with a full discretization.

2.2 Internal Structural Components

A. Trimmable Ballast System: Baseplate ("Ballast Rack")

To offset the effects of a changing center of gravity due to fuel mass loss during flight operation and equivalently maintain a constant longitudinal center of gravity, a trimmable moving ballast system has been developed and manufactured through Ames in-house efforts. The trimmable ballast system (Figure 8), situated across the length of the cabin floor of the MTRAP configuration, consists of two principal components: a baseplate (commonly referred to as the 'ballast rack') and a movable ballast box (Figure 9). In the trimmable ballast system, only the baseplate is considered to be a structural component within the internal structure of the craft. This item was modeled with a full discretization.

The 0.5" thick aluminum baseplate of the ballast system, connected redundantly at fifteen separate cabin floor tie-down points, runs longitudinally across the the center length of the UH-60A cabin floor between stations 265.5 through 398.0. It consists of large cabin floor mount with a slightly smaller track/rail overlay which serves as a track system upon which a movable ballast cart sits. The baseplate also serves as a mounting surface for the flight engineer's seat installation. The ballast cart is allowed to move longitudinally across the track as directed by a computerized control unit to compensate for the changing center of gravity due to the loss of fuel mass. The ballast rack is modeled structurally in the NASTRAN model as it is considered to contribute significant structural and mass effects to the cabin floor in concert with the baseplates/mounts of other flight related equipment. The baseplate weighs 376 lbs according to pre- and post-manufacture specifications by Sikorsky Aircraft. As a side note, we note that in the effort to maintain a predetermined center of gravity and gross weight configuration for the helicopter, a general arrangement for the longitudinal center of gravity of expansion program has defined the baseplate as a ballast item at station 333.20 .

B. Instrumentation Racks:

Flight Engineer Instrumentation Rack (Fwd Rt Cabin)
Center of Gravity (C.G.) Rack (Aft Central Cabin)
Instrumentation Panel (Aft Right Cabin)
Pallet Rack (Aft Left Cabin)

Due to the nature of comprehensive flight testing, a significant amount of on-board and user accessible instrumentation and computational equipment is required. Three instrumentation racks and one instrument panel have been installed inside the UH-60A cabin with attachments to their respective frames and bulkheads.

B.1 Flight Engineer Instrumentation Rack (Forward-Right Hand Side)

The first rack to be considered is the flight engineer's instrumentation rack located behind the starboard cockpit seat in the forward cabin area (Figure 10). The instrumentation rack is mounted through support beams situated at the station 247.0 frame which separates the cockpit and cabin sections. This assembly was fabricated by the Army Engineering Flight Activity (AEFA) for 1988 flight tests. The flight engineer's instrumentation rack has a self and equipment load weight of 75 lbs by previous AEFA estimates. This item was modeled with a partial but equivalent finite element discretization.

B.2 Center of Gravity (C.G.) Rack (Aft Central Instrumentation Rack)

One instrumentation rack (48.1 inches high) is centrally located against the transition section in the aft cabin (Figure 11). The C.G. Rack is intended to carry Rotating Data Acquisition System (RDAS) and C.G. installation equipment including TM signal conditioners, power supply and converter boxes, yaw and roll accelerometers, gyroscopes, and the other related electronics packages. The rack is an aluminum sheet assembly that resembles a three-shelf structure which sits above the aft end of the trimmable ballast baseplate at station 391.5, buttline 0.0. This component is composed of an upper and lower frame with adjustable shelf trays and is mounted at both the ballast rack aft end and the transition section wall. This instrumentation rack is considered to contribute minor structural stiffness and mass to the aft cabin section and is modeled through the full discretization method. The C.G. Rack was also recently designed and manufactured through Ames in-house efforts. Previous flight test efforts have used an AEFA built instrumentation rack which was similar to the one presently installed. The C.G. Rack serves to replace the AEFA instrumentation rack. By calculated estimates, the self-weight of the C.G. Rack is 35 lbs. The maximum equipment load of 125 lbs is specified in the design of the rack. By conservative estimate, 75% of this maximum load is taken as the actual equipment load during flight (ie. 93.75 lbs). Thus, the weight of the total component is 128.75 lbs. This type of approximation regarding percentage of the maximum equipment load is acceptable given that slight differences such as these in the overall mass of the rotorcraft model has been shown in previous studies to cause miniscule differences in the overall global modal response. This item was modeled with a full finite element discretization.

B.3 Instrumentation Panel (Aft-Right Hand Side)

Additional instrumentation is required for flight data acquisition and was stored on one instrumentation panel situated in the aft cabin (Figure 12). The instrumentation panel on the starboard side, next to the multiplexer and formatter, is composed of two separate steel panels between the station 370.0 and 398.0 frames. This assembly was fabricated by the AEFA for 1988 flight tests and is currently in place for MTRAP tests. The instrumentation panel with equipment load weighs 175 lbs by AEFA estimate. This item was modeled with a full discretization.

B.4 Pallet Rack (Aft-Left Hand Side)

A fourth instrumentation rack has been recently installed inside the aft cabin on the left side cabin wall between station 370.0 and 398.0 frames at baselines 28.75" through 36.0" (Figure 13). The three-shelved pallet rack is intended to store calibration boxes, power supply units, synchronization boxes, and all related hardware. It measures 40" in height with shelf area dimensions approximately 19.88" by 7.25". The pallet rack is mounted to the cabin floor with an aluminum baseplate of an area measuring approximately 292 square inches. Both the baseplate and pallet rack assembly is modeled in the finite element model as the entire component is expected to contribute minor structural stiffness and mass influencing frequency response results. The pallet rack is unique in comparison to the previously installed AEFA instrumentation rack in that it is mounted through a cabin floor baseplate unlike the AEFA rack which was mechanically fastened to the cabin wall frames and bulkheads. This item was modeled with a full discretization.

The component was designed and manufactured by NASA Ames to replace recently returned AEFA instrumentation racks. Previous flight test efforts have used the AEFA built instrumentation rack. The pallet rack has a calculated self-weight of 66 lbs. As with the C.G. rack, the manufacturing designs accounting for stress and failure criteria allow a maximum equipment load of 25 lbs. The total equipment load is used as the actual flight test load as the 25 lbs is a low estimate for the built-up structure. Thus, 90 lbs constitute the total weight of the component.

C. Static Frequency Converter Baseplate

The frequency converter is another flight component that requires a mounting surface (Figure 14). The tape recorder baseplate is a one-piece 0.125" aluminum sheet covering approximately 13.0" by 20.0 " in area. The frequency converter plate assembly is located on the right front side of the cabin floor behind the flight test engineer's instrumentation rack. It is fastened to the cabin floor at station 283.0 and centered about baseline 23.58. Four shock mounts on top of the baseplate support the static frequency converter. Based on UTTAS flight designs, this installation was redesigned and manufactured at NASA Ames. With shock mounts, the simple baseplate is estimated to weight 7.5 lbs. The static frequency converter has a self-weight of 80 lbs. This item was modeled with a full finite element discretization.

D. Adapter Plate Assembly

Many baseplates and mounts for self-enclosed instrumentation boxes are included in the MTRAP flight configuration and attached at a series of cabin floor tie-down points. These include mounts for power sources, multiplexers, etc. Although these component mounts will not contribute significantly to the structural stiffness, the sum of all these mounts in concert may "fine tune" the vibratory response of the cabin floor through their minor additive stiffness and mass contributions. These baseplates and mounts include the Adapter Plate Assembly (Figure 15). This item was modeled with a full discretization.

A single adapter plate assembly was designed and manufactured at NASA Ames to replace individual NASA/AEFA baseplates for the mounting of the following components:

Formatter/Multiplexer
Tape Recorder I
Tape Recorder II

The single 0.50" thick aluminum baseplate has several main cutouts due to weight considerations and is located on the right aft cabin floor in the right cabin door way. The plate assembly covers an area 110.75" by 27". between stations 329.0 and 397.0. Three component trays for the formatter, multiplexer, and tape recorders, are attached to the adapter plate through a series of shock mounts. The formatter, multiplexer, and tape recorders have significant weights and are considered to be important mass items as opposed to equipment load weights which are modeled differently. These differences will be elaborated upon in a later discussion regarding mass modeling. The self-weight of the adapter plate and assembly is 44.10 lbs by NASA Ames stress and failure design specifications.

We also note that a limited analysis of the formatter/multiplexer rack has been completed by NASA Ames Systems Engineering Division to determine safety and failure criteria for installation. For our purposes, this rack and its distributed self-weight was considered to be separate from the lumped masses of the formatter and multiplexer.

E. Over Fuel Cell Ballast Assemblies

To maintain a predetermined longitudinal center of gravity of the helicopter during flight test studies, several locations along the length of the UH-60A have been set aside for ballast support structures. Such locations for the support structures include the nose bay, the cabin floor, the aft cabin area, and tail section. The over fuel cell ballast assemblies are examples of such support structures located behind the aft cabin above the right and left hand side fuel tanks (Figure 16). Located at spaces between baselines +/-10.0 and +/- 30.0 on both the right and left sides of the aircraft center line, the over fuel cell ballast structure is composed of two identical tri-beam support/baseplate assemblies that may carry up to fifteen lead sheets (19.31" by 36.75" area baseplate each). Each assembly is capable of supporting 750 lbs of lead sheets to be treated equivalently as simulated equipment loads. The over fuel cell assemblies have a self-weight of 130 lbs each to ensure a gross ballast load of 1,760 lbs for both sides with the weight of the assemblies included. Because of the rigid design of this installation, the over fuel cell ballast assemblies are modeled with respect to stiffness in addition to mass. These installations were designed and manufactured at Sikorsky Aircraft. We note that under the general arrangement for a longitudinal center of gravity expansion program, the Over Fuel Cell ballast had been defined as a ballast item that may range between the full 1,760 lbs to as low as 274 lbs at station 421.0 It had often been the case, that no ballast was added to the assemblies. This item was modeled with a full discretization.

2.3 Mass Items

A. RDAS II Instrumentation System

The RDAS II Instrumentation System replacing the previous RDAS I system or 'MUX bucket' consists of various types of telemetry/computer hardware stored inside a cylindrical enclosure (Figure 17). The system is located at station, butt, and waterline (341.215, 0.0, 315.0). The RDAS enclosure is mounted to the top of the main rotor head. Although the RDAS II System may undergo slight mass modifications to suit future flight test needs, the system has been weighed at 133 lbs. RDAS II is not considered to make a structural contribution to the global or local fuselage structure. As with the previous RDAS I, the RDAS II instrumentation system was designed and manufactured through NASA Ames in-house efforts.

B. Pilot, Co-Pilot, Flight Test Engineer

Passenger weights are clearly defined as mass items contributing weight to the flight configuration solely. A individual weight of 200 lbs for the pilot, co-pilot, and flight test engineer or observer has been designated as an acceptable standard passenger weight. Both the pilot and co-pilot are located at station, butt, and water line coordinates (F.S. 227.10, B.L. 24.0, W.L. 234.70) and (F.S. 227.10, B.L. -24.0, W.L. 234.70) at right and left hand sides in the cockpit section respectively. Seated in the forward cabin, the flight test engineer is located at (F.S. 277.0, B.L. 0.0, W.L. 218.781) on the observer seat mounted on top of the forward section of the ballast rack. We note that under a general arrangement for the LCGEP, both the pilot and copilot would have been defined as ballast items at station 229.00 .

C. Full Fuel

Full fuel for the MTRAP configuration weighs 2,448 lbs by UH-60A Project Office estimates. This standard full fuel weight for most production UH-60A craft is divided into two equal weights corresponding the right and left hand sides of the fuel tank in the aft cabin. These locations correspond to global coordinates (F.S. 420.80, B.L. -

19.0, W.L. 221.90) and (F.S. 420.80, B.L. 19.0, W.L. 221.90). Fuel weight has not been generally accepted as a pre-determined number for past configuration studies. Previous configurations such as DAMVIBS have used a lower total fuel weight of 2,300 lbs as the configuration was considered for ground vibration tests only. As a side note, empty right and left hand side fuel tanks weigh 160 lbs each.

D. Laser Cube Assembly (2)

Several devices have been dedicated for purposes of telemetry. Among them are two laser cube assemblies mounted externally on both stub wings on the right and left hand sides (Figure 18). The right and left stub wing cube assemblies have been estimated to weigh 8 lbs each at locations (F.S. 256.25, B.L. 49.0, W.L. 205.2583) and (F.S. 256.25, B.L. 49.0, W.L. 205.2583) respectively. Both laser cube assemblies have been design and manufacture through NASA Ames in-house efforts.

E. Trimmable Ballast System: Movable/Adjustable Ballast Box Assembly

Although the baseplate/ballast rack is considered to contribute significant structural stiffness to the cabin floor, two subcomponents of the trimmable ballast system warrant modeling in terms of mass contribution only. These subcomponents include the observer seat with flight test engineer/observer weight and the ballast box assembly with added lead ballast. Developed and manufactured by NASA Ames, the movable/adjustable ballast box (Figure 9) serves as a welded enclosure for the addition of lead sheet ballast plates (each with 9.62" by 21.62" area and .62" thickness dimensions) up to a maximum of 2900 lbs (2,500 lbs for the MTRAP configuration) As fuel is used during a flight operation causing changes in the center of gravity, the controlled movement of this box allows the maintenance of a constant longitudinal center of gravity. It is operated by a self-attached gear motor along the track and guide rails on the baseplate. The assembly centrally occupies the track length between stations 290.0 to 398.0, between baselines -10.0 and 10.0 on the right left sides of the aircraft centerline. Although a structurally rigid component in itself, the ballast box is modeled with respect to mass only because it does not contribute structural stiffness to the cabin floor or to the global fuselage response. A single lumped weight of 3,163 lbs is used to represent the box assembly and the other equipment components mounted on the box assembly. This lumped weight includes the following:

Item	Weight (lbs)
Ballast Box Assembly	238.0
Guide Shaft	15.0
Screw Jack Assembly	5.0
Gear Motor Assembly	5.0
Lead Sheet Ballast	2,900.0
TOTAL	3,163.0 lbs

This lumped weight representation is located at global coordinates (F.S. 313.75, B.L. 0.0, W.L. 218.781). The ballast box assembly was designed and manufactured originally by Sikorsky Aircraft for UTTAS flight tests. Also, we note as in the case of the ballast rack previously described in section 2.2, that a general arrangement for the longitudinal center of gravity of expansion program has defined the ballast box assembly as a ballast item moving between stations 303.4 and 350.8 in the effort to maintain a predetermined center of gravity and gross weight configuration for the helicopter,

F. Observer Station Seat

Three seats are present on the MTRAP flight test configuration. Two of these seats belong to the pilot and co-pilot and are already included in the gross weight configuration while the third extra seat is used for the seating of an observer or flight test engineer. This third seat (Figure 19) is situated in the forward cabin and is mounted on top of the forward track end of the trimmable ballast rack. This member is considered to be a mass item since only its respective mounting surface, the ballast baseplate, is considered to contribute significant structural stiffness to the cabin floor. The observer station seat weighs 63.4 lbs denoted and is located at coordinates (F.S. 277.0, B.L. 0.0, W.L. 218.781) with the flight engineer/observer location. The seat was purchased from Simula, Inc.

G. Tape Recorder I, Tape Recorder II, Formatter, & HALPS Multiplexer

The adapter plate assembly previously described serves as a mounting surface for three individual equipment trays. Each tray is mounted to the adapter plate through a series of shock mounts. Two flight data tape recorders, a formatter, and multiplexer (Figure 20) are placed on these trays. The two recorders with their respective trays weigh 52.5 lbs each (the recorder at 50 lbs, equipment tray at 2.5 lbs) and occupy the first two forward trays. The locations of tape recorder I and II are (F.S. 337.875, B.L. 29.375, W.L. 212.156) and (F.S. 358.125, B.L. 29.375, W.L. 212.281) respectively. The formatter occupies the last aft cabin equipment tray with the HALPS multiplexer placed on top towards the forward portion of the formatter enclosure deck. The formatter and multiplexer together with its equipment tray weigh 226.9 lbs (the formatter at 143.0 lbs, the multiplexer at 78.9 lbs, and the larger equipment tray at 5.0 lbs). The HALPS enclosure was designed and manufactured at NASA Ames while the other internal equipment components were purchased or on loan. These subcomponents were treated as lumped masses and placed with the adapter plate assembly. The tape recorders each have their respective lumped masses while the formatter and multiplexer centers of gravity were computed and averaged commensurate to their mass contribution and separation distance such that a single lumped mass could be specified for the two sub-components. The centroid location of the formatter and multiplexer lumped mass has its global coordinate at (F.S. 379.149, B.L. 25.3167, W.L. 224.4573).

H. Over Fuel Cell Ballast

The over fuel cell ballast also requires a companion description to the external structural component, the over fuel cell ballast assembly. Ballast over the net self-weight of the ballast assembly could be modified depending upon the flight requirements for maintaining a predetermined longitudinal centroid of the helicopter. As previously described in the section dealing with internal structural components, each assembly on either the right or left hand side on top of the full cell has a self-weight of 130 lbs to which a maximum of 750 lbs of additional ballast may be supported. The additional ballast is placed approximately between locations (F.S. 400.5803, B.L. 21.2029, W.L. 242.542) and (F.S. 439.8803, B.L. 21.2029, W.L. 242.542) on the right side and

(F.S. 400.5803, B.L. -21.2029, W.L. 242.542) and (F.S. 439.8803, B.L. -21.2029, W.L. 242.542) on the left side. The assembly and lead ballast plates were designed and manufactured by NASA Ames.

I. MTRAP Instrumented Main Rotor Blades

Although rotor blades have not been considered as structural components in past DAMVIBS finite element analyses, the mass of the four rotor blades were included. A single blade weighs 211 lbs. The rotor head mass in the NASTRAN model is equal to the static non-flapping mass of the aircraft rotor head plus 50% of the instrumented main rotor blade flapping mass. Two of the four rotor blades are uniquely instrumented and were designed and manufactured by Sikorsky Aircraft.

An itemized summary of the flight components and their respective weights is presented in Table V. A description of optional flight components that have been used within the MTRA Program but that are not onboard the current configuration are presented in Appendix A-1 for reference. A practical worksheet detailing the sub components and weights layout may also be seen in Appendix A-2.

3. SUMMARY

In this section and evaluation and description of most important flight components have been summarized. Also, a list of flight components unique to the MTRAP Flight Configuration (over a baseline production configuration) has been generated. These components fall into one of three categories that specify their location and contribution in terms of stiffness and/or mass: 1) External Structural Components, 2) Internal Structural Components, and 3) Mass Items. Each component has been described with respect to its location in the global model, assessed in terms of its structural and/or weight importance, and considered with appropriate estimations of any ballast or flight payloads if applicable. The modeling method used to discretize the respective structural flight component was described.

VI. MODELING OF COMPONENTS

1. Objective

The effort to model the relevant flight components was conducted in three parts:

1) Evaluation of Current Flight Components
2) Gathering of Component Modeling Data
3) Finite Element Discretization of Component Data

A general description of these steps is described:

2. Evaluation of Current Flight Components

After the total list of flight components was made and each component categorized, the components were evaluated in terms of their individual contribution in significantly changing the structural and mass properties of the global response model. The modeling effort must ensure the correct discretization of additional finite element structures. Hence, a rigorous definition of the articles was necessary in order to address the following characteristics and determine their importance in the global model:

1) Complex structural cut-outs (fillets, minor curved surfaces)
2) Definition of tie-down points
3) Selection of finite element mesh size
4) Displacement boundary conditions at tie-down interfaces
5) Lumped mass modeling of small and large flight components (ie. ballast racks, and laser cubes mounts)
6) Lack of physical tests to validate FE model accuracy

3. Gathering of Component Modeling Data

With a list of those flight components that required structural modeling, a significant part of the modeling effort could be dedicated to the gathering of manufacturing blueprints and/or physical measurements and estimations. This was required to obtain necessary modeling data including the following: 1) component dimension data, 2) material property data, 3) connection or tie-down information, and 4) general weight and ballast layout information. Component dimension data includes sheet thicknesses, details regarding beam cross sections, overall component dimensions, and other information relevant to modeling the geometry of the given flight component. Material property data includes elastic moduli, Poisson's ratio, and other data regarding the mechanical behavior of the component material(s) also used in the finite element formulation. With regards to connection or tie-down information, data is required to determine how the component is fixed to the test vehicle so that displacement boundary conditions may be specified between respective nodes of the discretized flight test component and the existing finite element mesh of the UH-60A model. Information regarding the general weight and ballast layout on the test vehicle was gathered to determine the locations on the UH-60A model or on the individual flight components at which concentrated masses could be placed. All modeling data was obtained from design blueprints or found through direct physical measurements of the components on board the UH-60A test vehicle. Generally, cross referencing between these two main sources of data provided the best modeling estimates of a limited number of components where no formal information was listed. Other related references such as material property tables were additionally utilized. We also note that previous data from sources such as DAMVIBS and NASA/AEFA ground vibration testing and modeling have been useful (for example, in the determination of spatial locations of mass items).

4. Finite Element Discretization of Component Data

The UH-60 components were modeled using MSC NASTRAN [5]. The following is a description of the NASTRAN elements used to model these components. Based on the modeling data gathered for each respective flight component, a finite element mesh was defined with grid points (GRIDs) in terms of the basic coordinate system (COORD) of the UH-60A NASTRAN model:

The connectivity, material properties, and dimensional characteristics of structural members of the MTRAP flight components are discretized analytically through the formulation and selective combination of several basic finite elements. Elements, such as quadrilateral plates (CQUAD4s) used to model thin shell structures, are characterized by the coupling of bending and membrane stiffnesses. CQUAD4s are selected and implemented based on the respective flight component and its specific structural composition. Likewise, triangular CTRIA3 thin plate/shell elements can used in place of CQUAD4s to describe highly curved, warped, or swept surfaces or to represent nonrectangular sections in modeling difficult or complex geometries. CTRIA3 elements, like CQUAD4s, are also characterized by the coupling of bending and membrance stiffnesses and are thus subject to bending and twisting moments in addition to shear and normal forces.

Beam-type element are also required in the discretization of MTRAP flight components. CBAR or CTUBE elements may be used where needed to model items such as angled or hollowed cylindrical beams of uniform cross section. CBARs are uniaxial bar elements that may exhibit extension, torsion, and bending behavior and thus may be subjected to torque and bending moments in addition to shear and axial forces. CTUBEs are tubular elements describing beams of circular cross section that may undergo tension, compression, and torsion behavior.

For both thin-shell and beam-type elements, isotropic material properties, cross-sectional data, and other related element parameters are specified on MAT1 material property cards in association with PSHELL, PBAR, and PTUBE element property cards.

Multiple point constraint or MPC cards are used to define displacement relations between appropriate degrees of freedom. Other constraints such as those describing tie-down points between flight component and UH-60A mesh are also defined similarly. Concentrated masses (CONM2) reflecting flight component mass, cargo, or other ballast are defined and distributed at appropriate grid points (GRID) and may be connected respectively with rigid elements such as RBE3 if appropriate.

A graphical summation of the finite element components representing the structural flight items are presented in Figure 21. A detailed description of the modeling of each component is given below.

4.1 External Structural Components

A. Instrumented Test Boom

The finite element mesh modeling the instrumented test boom is described by 33 grid points and a total of 32 CTUBE elements. The test boom geometrically consists of a series of cylindrical tubes of various diameters and wall thicknesses and is modeled with CTUBE elements. Constraint relations describe the two rigid supports between the test boom and appropriate fuselage station frames This basic grid mesh for the component is presented in Figure 22. The number of each grid point is identified in the figure.

B. Instrumented LASSIE Bar

The finite element mesh modeling the LASSIE bar is described by 24 grid points and a total of 23 elements. Of these 23 elements, 21 are CTUBE elements and 2 are CBAR elements. The LASSIE bar grid point mesh is presented in Figure 23.

4.2 Internal Structural Components

A. Trimmable Ballast System: Baseplate ("Ballast Rack")

The finite element mesh modeling the Trimmable Ballast System (TBS) ballast rack is described by 479 grid points and a total of 350 elements. Of these 350 elements, there are 192 CQUAD4 quadrilateral elements, 100 CTRIA3 triangular plate elements, and 58 CBARs. The ballast rack is modeled in detail with CQUAD4 triangular plate elements to represent the extruded baseplate with its respective cutouts. The various guide angles and rails for the moving ballast box are also modeled with the observer seat tracks. These angle and rail elements are modeled with CBAR bar elements and connected to the baseplate through displacement relations that may be defined through MPC cards. The ballast rack in itself is 'tied down' at eleven points to the cabin floor through MPC relations at appropriate points consistent with the tie-down points defined on the ballast rack mesh. This mesh is presented in Figure 24.

B. INSTRUMENTATION RACKS:

Flight Engineer Instrumentation Rack (Fwd Rt Cabin)
C.G. Rack (Aft Central Cabin)
Instrumentation Panel (Aft Right Cabin)
Pallet Rack (Aft Left Cabin)

B.1 Flight Engineer Instrumentation Rack (Forward-Right Hand Side)

The finite element mesh modeling the flight test engineer's instrumentation rack is described by 20 grid points and a total of 16 elements. All 16 of these elements are CBARs. The major cross beams that run from the bottom to the top of the station frame and the two mounting beam surfaces in the forward right hand side section are modeled as they are the main structural feature with significant cross section and material stiffness relative to the instrumentation box which is supported by the cross beams. This item is modeled with an equivalent but partial discretization since the equipment box mounted is relatively much less stiffer than the major cross beams which may be modeled correctly with a small number of finite elements. The instrumentation rack is tied to the station frame ribs through the two mounting beam surfaces. This mesh is presented in Figure 25.

B.2 Center of Gravity (C.G.) Rack (Aft Central Instrumentation Rack)

The finite element mesh modeling the C.G. rack is described by 129 grid points and a total of 180 elements. Of these 180 elements, 96 are CQUAD4s and 84 are CBARs. The shelf angles, trays, and side panels are modeled with CBAR bar and CQUAD quadrilateral elements respectively. The C.G. rack is mounted to the top of the TBS ballast rack in the aft central cabin through a series of MPC displacement relations describing the appropriate six tie-down points. The C.G. rack component model is presented in Figure 26.

B.3 Instrumentation Panel (Aft-Right Hand Side)

The finite element mesh modeling the instrumentation panel in the aft right hand side of the cabin is described by 55 grid points and a total of 40 elements. Of these 40 elements, 36 are CQUAD4s and 4 are CBARs. The two separate upper and lower sections of instrumentation panel are modeled with CQUAD4 quadrilaterals as they are essentially single piece thin plates with miniscule cut outs mounted to the side cabin at various tie-down points (seven) on station frame ribs. An adjoining mounting beam angle separating the upper and lower sections is described by CBAR bar elements and is of significant area cross section, inertia, and material stiffness. The component model is presented in Figure 27.

B.4 Pallet Rack (Aft-Left Hand Side)

The finite element mesh modeling the pallet rack in the aft left hand side section of the cabin is described by 74 grid points and a total of 97 elements. Of these 97 elements, 38 are CQUAD4 quadrilateral elements, 3 are CTRIA3 triangular elements, and 56 are CBAR bar elements. The shelf angles, trays, and side panels of the pallet rack are modeled with CBAR bar and CQUAD4 quadrilateral elements respectively. The baseplate that serves as a mounting surface for the pallet rack is also modeled through CQUAD4 elements. MPC displacement relations describe the eight tie-downconnections between the rack and the mounting baseplate and also the those between the baseplate and the cabin floor skin. This component model is seen in Figure 28.

C. Static Frequency Converter Baseplate

The finite element mesh modeling the static frequency converter baseplate is described by 15 grid points and a total of 8 CQUAD4 quadrilateral elements. The thin baseplate is modeled exclusively with CQUAD4 quadrilateral elements and is considered to be a minor structural addition. MPC displacement relations are again used to describe two tie downs between the baseplate and the cabin floor. This component that occupies a very small space locally on the cabin floor is seen in Figure 29.

D. Adapter Plate Assembly

The finite element mesh modeling the adapter plate and assembly is described by 104 grid points and a total of 83 elements. Of these 83 elements, 55 are CQUAD4s elements and 28 are CTRIA3 elements. In a manner similar to the modeling of the TBS ballast rack, the adapter plate mono-structure with its respective cut outs is modeled with CQUAD4 and CTRIA3 elements. Four grid points describe respective tie-downs to the cabin floor skin. This component mesh is presented in Figure 30.

E. Over Fuel Cell Ballast Assembly (2)

The finite element mesh modeling each over fuel cell ballast assembly (right or left hand side) is described by 35 grid points and a total of 54 elements. Of these 54 elements, 24 are CQUAD4 elements and 30 are CBAR elements. The mounting beam surfaces and ballast support angles of significant area cross section and inertia/material properties are modeled with CBAR bar elements while the lead ballast plate support surface is modeled with CQUAD4 quadrilateral elements. Both RHS and LHS assembly models are presented in Figures 31 and 32 respectively.

4.3 Mass Items

RDAS II Instrumentation System
Pilot, Co-Pilot, Flight Test Engineer
Full Fuel
Laser Cube Assembly (2)
Trimmable Ballast System: Movable/Adjustable Ballast Box Assembly
Observer Station Seat
Tape Recorder I, Tape Recorder II, Formatter, & HALPS Multiplexer
Over Fuel Cell Ballast
MTRAP Instrumented Main Rotor Blades

The distribution of structural and nonstructural weight to the appropriate areas of the finite element model is often a tedious and time consuming task. In the case of rotorcraft, most weight is often of a nonstructural nature. Automated procedures with a NASTRAN interface program are often used in industry to generate the necessary NASTRAN input data. In this current study, special mass items such as flight components listed above and seen in Table V were entered into NASTRAN code separately "by hand" to represent unique items or different weight configurations. In each case of the respective mass item, it was determined that the mass of the component could be represented either as 1) a single point mass located at its center of gravity (F.S., B.L., W.L.) with respect to the global coordinates of the UH-60A model or 2) as a series of point masses distributed uniformly across the appropriate component element mesh surface or line. The mass items mentioned above were modeled in one of these two ways such that 1) an item was specified by a CONM2 concentrated mass at a GRID point corresponding to the item's center of gravity and rigidly connected to a nearby global model with RBE3 elements or 2) the mass of the item was divided into smaller CONM2 concentrated masses and assigned to the corresponding GRID point or points on the existing finite element mesh. For example, the full fuel mass is divided into two equal point masses corresponding to fuel located on right and left hand sides. The two centers of gravity corresponding to these fuel parts is specified by a grid point and connected to the nearby UH-60A global mesh with rigid elements. In another example, the 376 lbs of the TBS ballast rack self weight was divided equally into 78 point masses and distributed uniformly among 78 separate existing grid points along the central portion of the ballast rack finite element mesh. These items were discretized in a manner similar to that used in the previous study by the authors.

For the most of the UH-60A mass model items however, lumped masses are generated by first creating a computer file listing the weight and inertia properties of approximately 5,000 components (both structural and nonstructural) in a MIL-STD tabulation form. Hence, a description of the item (ie. pilot, cabin seat, frame section, etc.), its mass, centroid location, and mass moments of inertia, in terms of the model coordinate system are stored. Second, a volume describing the entire aircraft, again using the model coordinate system, is defined in the mass model generation program and divided into a greater number of smaller, equally sized subvolumes or regions. The interface program assigns each mass item a location in the model volume and respective region based on its centroidal coordinates. Next, the program calculates a new center of gravity and single lumped mass from the summation and computation of mass items data for each region. Finally, NASTRAN input data lines are written specifying a grid point (GRID) and concentrated mass (CONM2) at the new centroid of each region. This process is repeated for each region over the entire volume. An RBE3 rigid element is created for each concentrated or lumped mass to connect the concentrated mass item to the structural model. The RBE3 element allows the mass to undergo components of motion calculated from the average summation or weighted average of other nearby structural grid points. This mass modeling procedure is depicted in Figure 33. The volume and region size and shape may be arbitrarily chosen based upon the unique structural and mass configuration of different aircraft. For example, the UH-60A NASTRAN model by Sikorsky uses a finite pie shaped inertia region, while Boeing-Vertol uses a rectangular box shape for their finite element models. The combination of the GRID, CONM2, and RBE3 elements are used frequently in the definition of mass items. Alternatively, mass may be specified directly at a pre-existing grid point if the mass occupies that point on the global structure.

5. Summary

The modeling of additional structural/mass components may be divided into three parts: 1) Evaluation of Current Flight Components, 2) Gathering of Component Modeling Data, and 3) the Finite Element Discretization of Component Data. Flight components are categorized in various groups based on their contribution in terms of structural stiffness and additional weight. Component modeling data is generated using existing blueprint or manufacturing data and physical measurements. Component data is used to generate the basic finite element meshes for each respective component.